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OPTIMIZING CRACK--GROWTH RESISTANCE IN ENGINEERING ALLOYS.(U)

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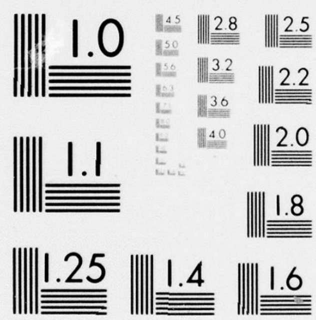

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Optimizing Crack-Growth Resistance in Engineering Alloys

T. W. CROOKER

Metals Performance Branch
Engineering Materials Division

April 18, 1977

NAVAL RESEARCH LABORATORY
Washington, D.C.

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Designers often cannot prevent cracking in machinery components or structural members. Uncontrollable factors such as undetected manufacturing defects and unforeseen service conditions can initiate cracking that affects safety, reliability, and maintenance. One way designers can compensate for these is in selection of alloys for optimum crack-growth resistance. Enhancement of crack-growth resistance is now an active area of material research. This report summarizes recent information that can help design engineers with problems involving stress-corrosion cracking and fatigue crack growth.

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CONTENTS

OPTIMIZING CRACK-GROWTH RESISTANCE IN ENGINEERING ALLOYS

INTRODUCTION

Design engineers often must reckon with the fact that the product of their efforts will become flawed (cracked) through improper manufacture, unforeseen use, or simply extended service. Recognition of this fact and its implications for safety, reliability, and maintenance is leading toward standards and codes that impose design requirements for the fracture mechanics analysis of cracking behavior. Perhaps the most notable example is the Air Force requirements for aircraft structural integrity [1]. Cracking behavior is also assuming a greater role in design of space vehicles, advanced ships, nuclear systems, offshore structures, and civil transportation systems.

However, these formal regulations cannot replace the need for good basic design engineering. For instance, alloy selection is a primary means by which design engineers can cope with cracking phenomena from the outset. There are wide variations in crack-growth resistance among engineering alloys. Frequently, there can be significant variations within a given generic class of alloys (e.g., 4340 steel or Ti-6Al-4V) as a function of metallurgical variables that can be specified and controlled.

Currently substantial government-funded research programs are under way to improve the crack-growth resistance of existing alloys and develop new alloys with greater crack-growth resistance. This report presents recent information on optimizing crack-growth resistance in existing engineering alloys. Two types of cracking phenomena will be considered: aqueous stress-corrosion cracking and fatigue.

STRESS-CORROSION CRACKING

Design Approach

Eliminating or minimizing stress-corrosion cracking (SCC) can often be a designer's first line of defense against crack growth. For the purposes of this discussion, SCC can be defined as any crack-growth mechanism that occurs in metals under sustained tensile stress in an aqueous environment. However, in its broadest sense the term includes both crack-initiation and crack-propagation mechanisms and can occur in a wide range of organic and inorganic environments. The information presented in this paper will be largely restricted to results from extensive NRL studies of SCC in marine environments.

The primary analytic approach to both SCC and fatigue crack growth uses linear-elastic fracture mechanics. The fracture mechanics parameter that characterizes SCC resistance is termed K_{Iscc} [2]; it defines a threshold crack-tip stress state below which SCC will not occur for a specific combination of material and environment. K_{Iscc} values are determined experimentally, primarily from sustained-load tests conducted on relatively small precracked specimens [3].

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Thus, from a design point of view, SCC is approached on a *prevention* basis, much as endurance-limit fatigue characteristics are applied in design to prevent fatigue cracking. Current SCC technology provides designers with relatively little useful information on the rates at which SCC cracks grow under various conditions once the K_{Iscc} threshold level has been exceeded at the crack tip. However, given a K_{Iscc} threshold value for a given combination of material and environment, the designer can apply conventional fracture mechanics solutions [4] to calculate the conditions of stress level and flaw size defined by that K value for the crack geometry of interest.

Herein lies the primary value in using fracture mechanics parameters to describe crack-growth phenomena. The results of laboratory characterization tests conducted on precracked specimens of convenient size and geometry can be described in terms of crack-tip stress-intensity factor K. K is a geometry-independent parameter that, in turn, can serve as a normalized basis for computing conditions of crack size and stress level in specific geometries relevent to design problems.

Criteria for Materials Selection

The most important single factor in selecting materials to resist SCC is strength level. Stress-corrosion cracking is nearly always confined to high-strength alloys. In steels, it is seldom observed in base plate materials with yield strengths below 120 ksi (827 MPa) or in weld metals with yield strengths below 80 ksi (552 MPa). At lower strength levels, titanium and aluminum alloys also tend to be immune to SCC. Thus, the first approach to SCC prevention available to the designer is simply to avoid the use of high-strength alloys whenever possible.

If high-strength alloys are clearly necessary to achieving a design requirement, considerable latitude is often available to assure that optimum SCC resistance is retained for a specific materials application. Figure 1 illustrates the manner is which K_{Iscc} values decrease with increasing yield strength (σ_{ys}) in heat-treated 4340 steel [5]. Because of the interplay between K_{Iscc} and σ_{ys} in high-strength alloys, the ratio K_{Iscc}/σ_{ys}, which is proportional to critical crack size in fracture mechanics equations, becomes a useful parameter in judging SCC sensitivity. Experience has shown that for K_{Iscc}/σ_{ys} values below 0.3, critical crack sizes to initiate crack growth in SCC become so small that conventional nondestructive inspection cannot assure SCC prevention. Conversely, only for K_{Iscc}/σ_{ys} ratios in excess of 0.7 do critical crack sizes become large enough to assure highly reliable SCC prevention. For K_{Iscc}/σ_{ys} ratios between 0.7 and 0.3, considerable care should be taken to assure SCC prevention. These three regimes of SCC behavior are denoted by "high," "intermediate," and "low" SCC resistance in Fig. 1.

The reader will note in Fig. 1 that, for 4340 steels, nearly all K_{Iscc} values at σ_{ys} levels in excess of approximately 180 ksi (1241 MPa) are below the 0.3 ratio line. Only for σ_{ys} values below about 140 ksi (955 MPa) is the 0.7 ratio line exceeded. It is also of interest to note that the falloff in K_{Iscc} values can be rather steep above σ_{ys} = 120 ksi (827 MPa) in 4340 steel. This K_{Iscc} transition behavior owing to strength level is common among high-strength steels and has led to a materials selection concept recently instituted by the Navy wherein a maximum permissible yield strength is specified for SCC-critical

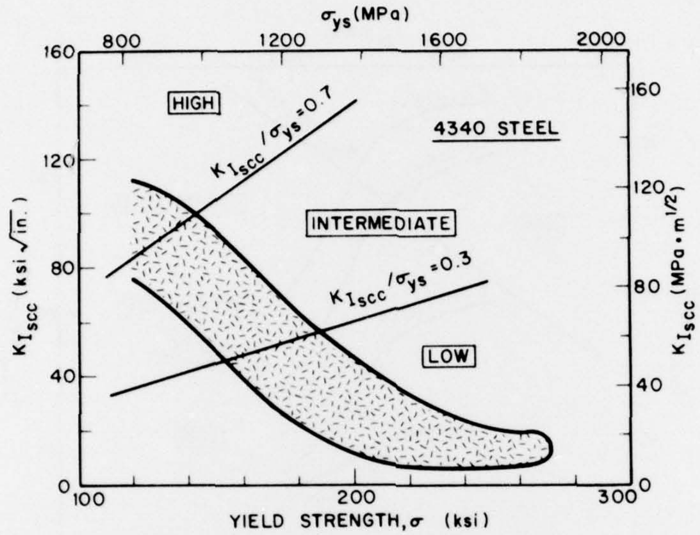

Fig. 1—Stress-corrosion cracking (SCC) characteristics of 4340 steel as a function of yield strength (σ_{ys}) [5]. Regions of high, intermediate, and low SCC resistance are denoted by specific K_{Iscc}/σ_{ys} ratios.

materials applications. Where strength level specifications are invoked, the more conventional practice is to specify a minimum strength or hardness. However, where SCC is operative, allowing σ_{ys} values to float upward without specified limits can have disastrous consequences.

Figure 2 [6] illustrates another important point of which designers should be aware in materials selection and application. Cathodic protection applied to minimize general surface corrosion can have a pronounced detrimental effect on SCC resistance in steels. The curves in Fig. 2 are for heat-treated 17-4 PH steels under freely corroding conditions and also coupled to several types of sacrificial anodes to achieve cathodic protection. In addition to the falloff in K_{Iscc} values with increasing σ_{ys} values, a marked decrease in K_{Iscc} values with increasingly negative electrochemical potentials resulting from cathodic protection can be seen. This sensitivity of K_{Iscc} to negative potential is common among high-strength steels. Thus, designers who use ferrous materials under corrosive conditions must balance the benefits of suppressing general surface corrosion at the possible expense of SCC resistance.

The influence on K_{Iscc} characteristics of metallurgical factors other than strength level achieved through heat treatment are not clearly understood. However, this is not to suggest that metallurgical factors do not exert a pronounced influence on K_{Iscc} characteristics. This fact is very clearly illustrated in Figs. 3 and 4 [7], which are zonal summary plots of K_{Iscc} vs σ_{ys} for generic types of high-strength steels and titanium alloys, respectively. These plots indicate that for a given level of σ_{ys}, K_{Iscc} can vary by as much as a factor of 5 in titanium alloys and a factor of 10 in steels. Obviously, certain

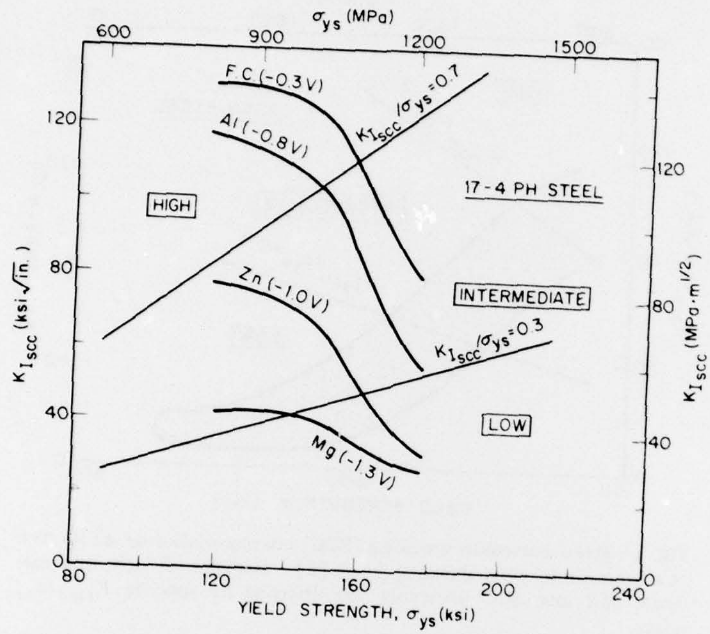

Fig. 2—Effect of electrochemical coupling for cathodic protection on the SCC resistance of 17-4 PH steel heat treated to various strength levels [6]. The upper curve illustrates freely corroding conditions, and the lower curves reflect the effects of coupling to aluminum, zinc, and magnesium anodes, respectively.

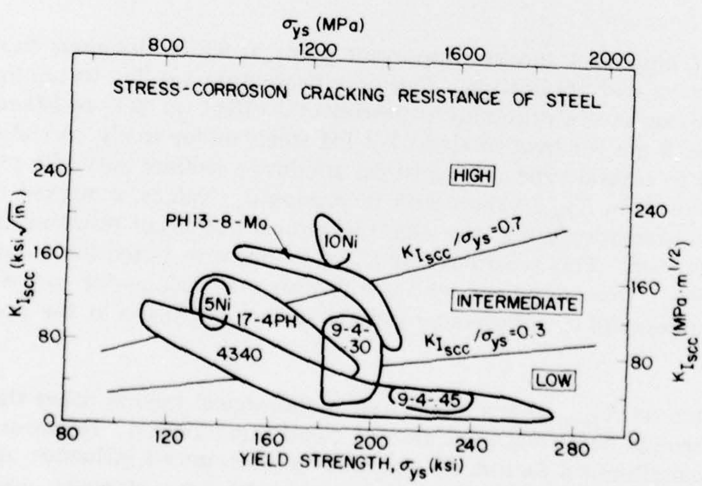

Fig. 3—Summary of SCC characteristics of selected high-strength steels [7]

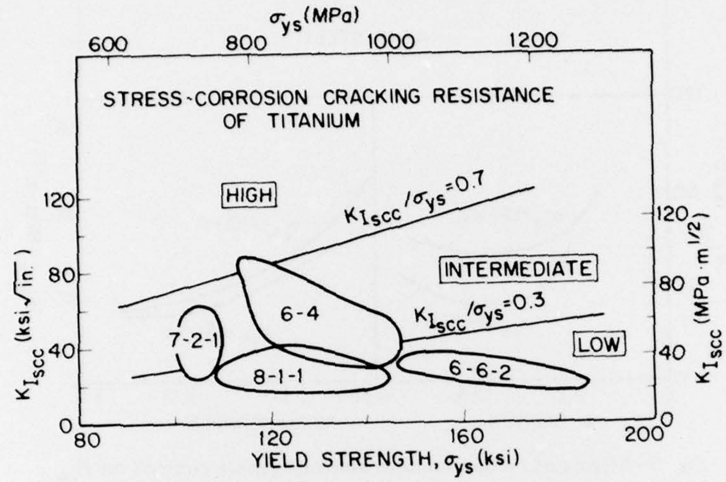

Fig. 4—Summary of SCC characteristics of selected high-strength titanium alloys [7]

generic classes of alloys have much greater inherent SCC resistance than others. Nevertheless, apparent benefits in SCC resistance must be balanced against other aspects of overall corrosion characteristics in making optimum alloy selections. For instance, 17-4 PH and PH 13-8-Mo steels, which can exhibit rather good K_{Iscc} characteristics, are highly susceptible to crevice corrosion, which hastens SCC initiation.

One point of caution for design engineers is apparent in these summary plots; the K_{Iscc} properties of commonly used generic materials such as 4340 steel and Ti-6Al-4V can vary widely in response to strength level as well as other metallurgical factors. Sandoz [8] has made a systematic study of the effects of alloying elements on the K_{Iscc} characteristics of martensitic high-strength steels. However, since many alloying elements strengthen steels and thus depress K_{Iscc} values, Sandoz's comparisons were made for variations in alloy content at relatively uniform strength levels. Among alloying elements, only carbon and manganese were found to affect K_{Iscc} characteristics (Fig. 5). Also, processing by vacuum melting to maximize purity has been found to exert only negligible effects on the K_{Iscc} characteristics of steels [5]. This is in marked contrast to the fracture toughness characteristics of high-strength steels, which are dramatically improved by vacuum melting to achieve high purity [9]. Among high-strength titanium alloys, both fracture toughness and SCC resistance are inversely proportional to the atomic percent of aluminum plus interstitial oxygen [10,11]. Therefore, Ti-8Al-1Mo-1V alloys tend to have lower K_{Iscc} levels than Ti-6Al-4V alloys, and the K_{Iscc} characteristics of Ti-6Al-4V alloys can vary widely as a function of chemistry and microstructure, as shown in Fig. 4.

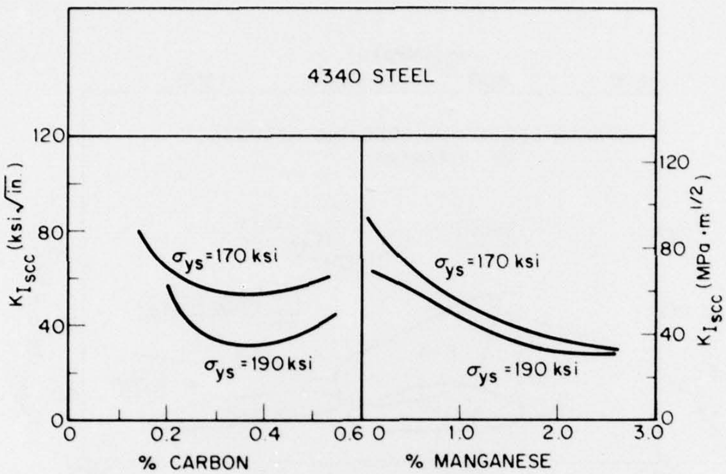

Fig. 5—Effects of carbon content and manganese content on K_{Iscc} characteristics of 4340 steel at two yield strength levels [8]

FATIGUE CRACK GROWTH

Design Approach

Traditionally, the designer has approached fatigue on a prevention basis, i.e., materials are considered to be flaw-free throughout the duration of useful service life, and cracking constitutes a failure criterion. More recently, however, fracture mechanics fatigue design concepts [12] have provided designers with an analytical ability of dealing with the reality of the existence of cracks in machinery components or structural members throughout their service lives.

For the many situations in which this approach to fatigue design is applicable, prevention of fatigue failure relies on containment of crack growth within specified safe limits. For situations in which in-service inspection and repair are possible, safe service intervals are established between scheduled maintenance. Where in-service inspection and repair are not feasible, a more conservative criterion must be established: anticipated defects must not grow to a dangerous size during the service life of the component or member. The consequences of premature failure are weighed in establishing the degree of conservatism required for a particular application. The rationale and methodology for using fracture mechanics fatigue design are discussed in detail in Refs. 12 and 13.

The characteristic material property that describes fatigue crack-growth resistance is per-cycle crack-growth rate da/dN as a function of fracture mechanics fatigue parameter ΔK [12]. Relationships of da/dN vs ΔK are commonly of an exponential form such that

$$da/dN = C\,(\Delta K)^m \tag{1}$$

and thus most often appear as straight-line plots on log-log coordinates. Therefore, for the purposes of this report, graphs of fatigue crack growth resistance will appear mainly as log-log plots of da/dN vs ΔK.

Criteria for Materials Selection

Unlike SCC, yield strength, per se, has little effect on the fatigue crack-growth resistance of engineering alloys, which is determined by the micromechanisms of crack propagation. It is a common misconception that all fatigue is uniquely characterized by the formation of surface striations. Actually, fatigue crack growth can occur by many mechanisms, including stration formation, microvoid coalescence (dimpled rupture), microcleavage, intergranular separation, and various types of faceted behavior [14-18]. In fact, striations are more the exception in fatigue than other, less familiar, mechanisms which actually occur more commonly in fatigue [16]. Widespread failure to recognize and understand the diverse nature of fatigue crack-growth mechanisms continues to hamper many attempts at failure analysis, which all too often rely on the presence of visible striations as the sole evidence of a fatigue mechanism.

The micromechanisms of fatigue-crack growth are controlled by many metallurgical factors, among which strength level, per se, is of relatively minor importance. For example, Barsom [19,20] has reported on fatigue crack propagation in a variety of steels ranging in yield strength from 36 to 300 ksi (248-2070 MPa). His results show that, in the absence of high mean stresses (cyclic loading near zero-to-tension) and in the absence of a corrosive environment (room air), all the data fall within two narrow scatterbands (Fig. 6). One scatterband includes data for high-strength martensitic steels, and the other includes data for lower strength ferrite-pearlite steels. Further, the modestly enhanced crack-growth resistance in the ferrite-pearlite steels is attributed to crack branching, which is induced by microstructural effects [20]. The uniformity of results illustrated in Fig. 6 is undoubtedly because the materials and loading conditions employed resulted in a largely uniform fatigue-crack growth mechanism that is not necessarily sensitive to strength level, viz, ductile striations.

Conversely however, the lack of any improvement in fatigue crack-growth resistance with increasing yield strength places the higher strength alloys at a tremendous disadvantage in fatigue resistance. With no improvement in properties, the higher working stresses demanded of these high-performance alloys can result in much faster rates of crack propagation and, as a consequence, much more rapid fatigue failure. Therefore, effective crack-growth resistance is diminished in high-strength alloys, even though intrinsic fatigue crack-growth resistance is little affected by yield strength per se.

Evidence of the type presented in Fig. 6 often leads to the generalization that "all materials are the same in fatigue." This can be a poor rule to rely upon. For instance, there is considerable recent evidence to suggest that fracture toughness can have a very pronounced, if indirect, effect on fatigue crack-growth resistance. Richards and Lindley [14] reported on fatigue-crack propagation in a variety of steels ranging in yield strength from 40 to 190 ksi (275-1300 MPa). They correlated their results with fractographic observations of the mode of separation involved in each material, as summarized in Fig. 7.

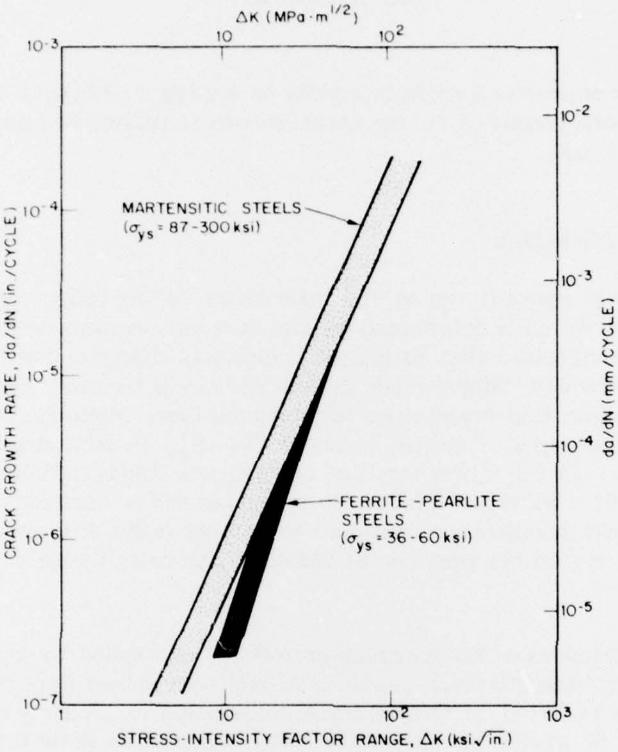

Fig. 6—Fatigue-crack propagation characteristics of selected steels ranging in yield strength from *36 to 300 Ksi* **(248-2070 MPa) [19,20]**

Where the operative mechanism was striation formation (high to intermediate fracture toughness, low mean stress) crack-growth rates for a given level of cyclic stress, as characterized by ΔK, varied by no more than a factor of 5. However, where lower energy mechanisms became operative (lower fracture toughness, higher mean stresses) crack-growth rates could vary by as much as a factor of 100. The role of low-energy cracking mechanisms, such as microcleavage, in accelerating crack growth in low-toughness steels has been documented also by other investigators [15,17]. Therefore, metallurgical factors that tend to improve fracture toughness in engineering alloys (high purity, low carbon content, fine grain size, homogeneous microstructures) can in addition optimize fatigue-crack-growth resistance.

An example of the variation in fatigue-crack-growth resistance that can accompany metallurgical variations is shown in Fig. 8. Throop and Miller [21] have reported on the variation of a wide range of mechanical properties in 4340 steel with heat treatment, including fatigue-crack growth rates. As shown in Fig. 8, crack-growth resistance does change significantly in 4340 steel with broad changes in yield strength, fracture toughness, and microstructure. Based upon their results, tempering near 1000°F (538°C) produces optimum fatigue crack-growth resistance in this generic class of alloys.

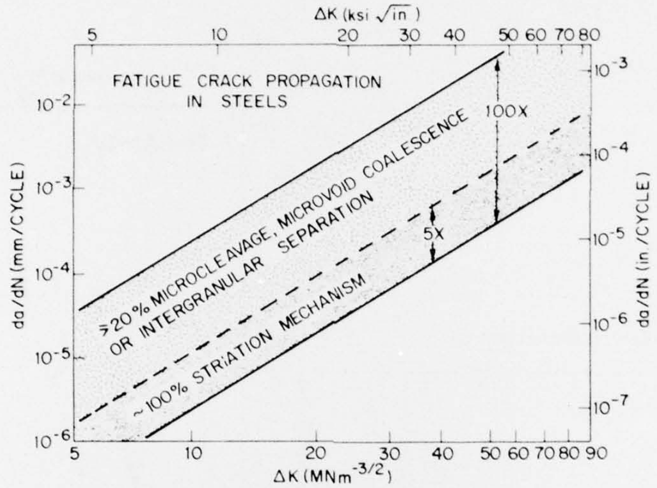

Fig. 7—Relationship of fatigue-crack-growth rates to fatigue *cracking mechanisms for selected steels* ranging in yield strength from 40 to 190 *Ksi* (275-1300 MPa) [14].

Current research aimed at optimizing fatigue-crack-growth resistance goes beyond merely pointing out the undesirable characteristics of existing materials and is aimed at developing new principles for achieving higher plateaus of crack-growth resistance in engineering alloys. A good example of such efforts is illustrated in Fig. 9. At present, titanium alloys appear particularly susceptible to enhancement of crack-growth resistance. One means of accomplishing this in these alloys is through microstructural modification by heat treatment. Figure 9 [18] illustrates the fatigue-crack-growth characteristics of a commercial-purity Ti-6Al-4V plate in the as-received mill-anneal condition, as commonly used in machinery and structural applications, and after receiving a beta anneal heat treatment. The microstructural modification induces a crack-front bifurcation mechanism (Fig. 10), which reduces crack-growth rates by as much as a factor of 10 in this alloy. Other effects of this heat-treatment procedure on mechanical properties include a modest reduction in yield strength and a large increase in fracture toughness.

Highly significant differences are also observed among engineering alloys with regard to crack-growth resistance in corrosion fatigue [22]. Although detailed discussion of this aspect lies beyond the scope of this report, several brief generalizations may be helpful to design engineers. First, some guidance with regard to corrosion fatigue can be obtained from K_{Iscc} characterization. Alloys highly sensitive to SCC seldom perform well under conditions of corrosion fatigue. However, this is not the whole picture. Widely used low-strength alloys, such as low-alloy steels, that are immune to SCC remain highly affected by corrosion fatigue [23]. Stress-corrosion cracking and corrosion fatigue bear many similarities mechanistically, but from a phenomenological point of view they are distinct in many respects. It could be a grave mistake to dismiss consideration of corrosion fatigue simply because an alloy is thought to be immune to SCC. Also, like SCC, corrosion fatigue-crack growth can be strongly affected by electrochemical potential in ferrous alloys [22,23].

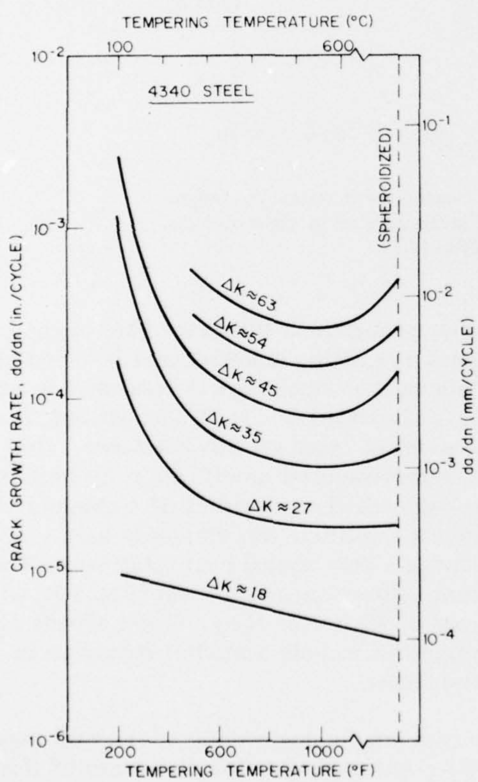

Fig. 8—Relationship of fatigue-crack-growth rates to tempering temperature for 4340 steel [21]. Indicated values of ΔK are in units of $Ksi\sqrt{in.}$ (1 $Ksi\sqrt{in.}$ = 1.1 MPa·$m^{1/2}$).

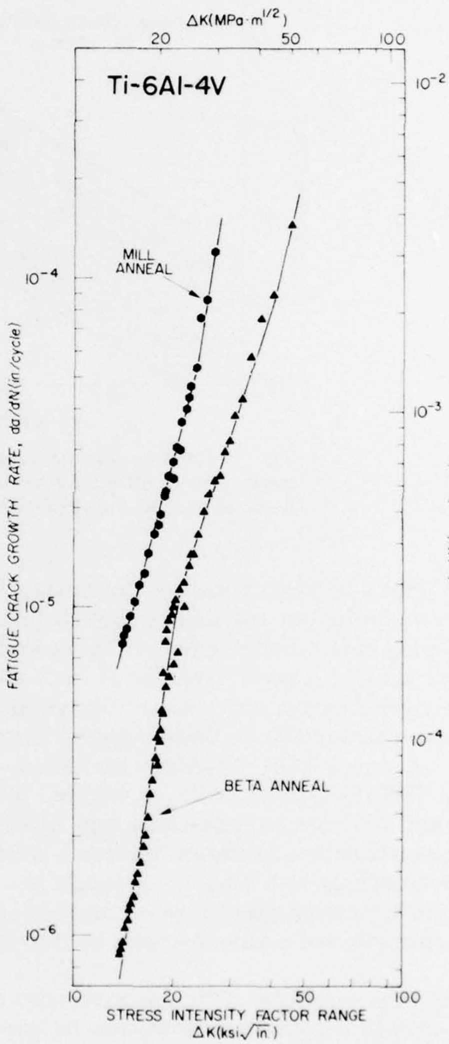

Fig. 9—Enhancement of fatigue crack-growth resistance in Ti-6Al-4V resulting from beta-anneal heat treatment [18].

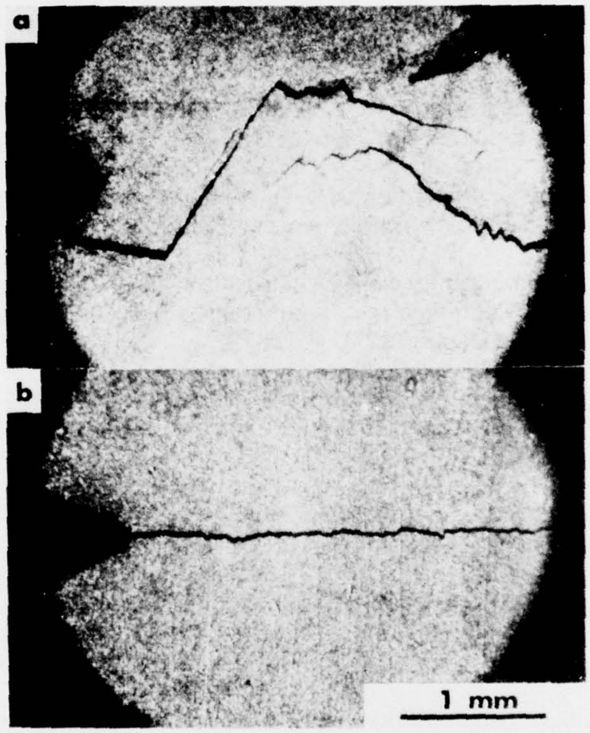

Fig. 10—Modes of fatigue crack growth in (a) beta-annealed Ti-6Al-4V and (b) mill-annealed Ti-6Al-4V [18].

SUMMARY

One of the best means by which designers can supplement analytic design procedures to minimize crack growth in engineering alloys is through proper materials selection. Both stress-corrosion cracking and fatigue-crack growth can be strongly influenced by metallurgical factors. Alloy chemistry, melting practice, and heat treatment all can have pronounced effects on crack-growth resistance. The criteria outlined in this report can provide helpful guidelines to design engineers seeking to recognize and minimize problems of crack growth.

ACKNOWLEDGMENT

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